A tri-generation plant fuelled with olive tree pruning residues in Apulia: An energetic and economic analysis

A tri-generation plant fuelled with olive tree pruning residues in Apulia: an energetic and economic analysis.

Riccardo Amirante*, Maria Lisa Clodoveo**, Elia Distaso*, Francesco Ruggiero***, Paolo Tamburrano*+

* Department of Mechanics, Mathematics and Management (DMMM), Polytechnic of Bari, Via Re David 200, 70126 Bari, Italy

** Department of Agro-Environmental and Territorial Sciences (DISAAT), University Of Bari, Via Amendola 165/A, 70126 Bari, Italy

*** Department of Civil Engineering and Architecture (DICAR), Polytechnic of Bari, Via Orabona, 70126 Bari, Italy

+ Corresponding author. Email: paolo.tamburrano@poliba.it, +39 0805963470.

Abstract

This paper presents the energetic and economic analysis of a virtuous example consisting of a tri-generation system fuelled only with olive tree pruning residues and planned to be located next to Bari Airport (Apulia, Italy). The main goal is to demonstrate the feasibility and convenience of producing cooling, heating and electrical power from olive tree pruning residues in those regions characterized by a high availability of this kind of biomass, such as Apulia. A strategic location was selected, namely Bari Airport (Apulia), and this paper demonstrates the economic convenience of installing a commercially available Organic Rankine Cycle (ORC) unit of 280 kW_e that is capable of satisfying the thermal demands of the airport, with the addition of an absorption chiller for air conditioning in the airport buildings. First it is verified that the quantity of oil tree pruning residues available in the area surrounding the airport fully can satisfy the plant demand of feedstock. Then a detailed description of the components of the plant is provided. The performance of the plant is therefore evaluated in order to assess the thermodynamic competitiveness of a tri-generative system fuelled with this type of biomass. Finally, a detailed economic analysis is carried out with the aim of demonstrating the advantages that the plant can assure in terms of payback period (PBP), net present value (NPV) and internal rate of return (IRR). Two different typologies of government incentives are considered. In both of which, the PBP is 6 years with an IRR of about 21% and this points out the great economic attractiveness of the project. From an ecological point of view, the plant can ensure a remarkable reduction in CO_2 emissions.

Keywords

Agricultural residues, tri-generation, Organic Rankine Cycle, economic analysis.

Nomenclature

a	*potential availability of residues*	
C_c	*chipping cost*	*[€/t]*
C_f	*fuel cost required for the transportation*	*[€/t]*
$C_{feedstock}$	*overall cost for feedstock procurement*	*[€/year]*
C_h	*harvesting cost*	*[€/t]*
C_l	*cost for loading and unloading the feedstock*	*[€/t]*
C_t	*transportation cost*	*[€/t]*
f	*pruning frequency per year*	
H_{dry}	*lower heating value of dry biomass*	*[kcal/kg]*
H_i	*lower heating value of wet biomass*	*[kcal/kg]*
h	*enthalpy*	*[kJ/kg]*
P	*pressure*	*[bar]*
P_{el}	*total electrical power*	*[kW]*
P_m	*weight of the feedstock transported*	*[t]*
$\dot{Q}_c$	*total useful cooling power*	*[kW]*
Q_{ol}	*mass of olives per year*	*[t/year/hectare]*
Q_{pr}	*mass of wet by-product (pruning residues)*	*[t/year/hectare]*
$\dot{Q}_{th}$	*total useful thermal power*	*[kW]*
T	*temperature*	*[°C]*
U	*percentage of humidity*	
Y	*ratio of the by-product to the olive yield*	
$\dot{m}_b$	*mass flow rate of fuel*	*[t/year]*
η_{el}	*overall electrical efficiency*	
η_g	*total efficiency*	

Acronyms

CCP	*combined cooling and power*
CHP	*combined heating and power*
CCHP	*combined cooling, heating and power*
IRR	*internal rate of return*
NPV	*net present value*
PBP	*payback period*

1. Introduction

For over twenty years, governments have taken a number of actions to solve the environmental problem concerning greenhouse gas emissions and global warming caused by the excessive consumption of fossil fuels. Energy policies implemented to date have been promoting renewable energy exploitation, providing full support by means of a number of incentives [1]. Such policies have already led to a significant change in the energy mix, which is continuously replacing conventional fuels with renewable energy sources. European countries planned to meet the 2020 targets on renewable energies thanks to such a relevant paradigm shift in renewable energy exploitation [2]. Biomass is a form of renewable energy that can effectively be utilized to reduce the impact of the energy production from fossil fuels on the global environment and can be converted into useful forms of energy by using different processes. Several techniques, plants and devices for extracting energy from waste biomass are available. The techniques for energy extraction from waste biomass can be grouped in the following “families”: Combustion, Pyrolysis/Gasification, Bio-processing. Biomass energy systems can generally provide several advantages such as a low carbon footprint and a lower delivered energy cost compared to fossil fuels. In biomass-fuelled power plants the electricity generation is usually coupled with the production of heating and/or cooling with the aim of increasing the overall efficiency, since the electrical efficiency is low in the plants fuelled with biomass.

Despite the energetic use of agricultural wastes can play an important role in reducing the consumption of fossil fuels, such a practice is not so widespread as expected in those regions having large availability of agricultural residues [3]. This paper is focused on a particular type of agricultural residues largely diffused in farms of the Mediterranean region, namely olive tree pruning residues, and aims to demonstrate that their energetic use can be very profitable in a tri-generation system, also thanks to the recent advances both in the tri-generation technology and in mechanical and management systems for harvesting, packaging and transportation [4]. It is planned to realize the tri-generative power plant in a region having a large quantity of oil olive crops, namely Apulia (south of Italy). The plant will be capable of satisfying the entire thermal and cooling demands of the buildings of Bari Airport as well as part of the electrical energy required by the Airport.

This paper aims to assess the feasibility and profitability of this system for tri-generation from the direct combustion of olive tree pruning residues. As starting point the availability of biomass in Apulia, particularly in the zone nearby the plant location, is quantified and compared with the needed amount of feedstock for the plant operation. Then the components of the proposed tri-generative plant are described in details. A thorough economic analysis is finally exposed in order to evaluate the economic convenience of the project.

In conclusion an estimation of the annual quantity of CO_2 that can be saved by the proposed plant is also provided.

2. The agro-energetic Apulian model

2.1 Potential of olive tree pruning residues for energy generation in the Mediterranean region

The simultaneous generation of electricity, heating and cooling from olive tree pruning residues in tri-generative plants can be instrumental in increasing energy production from renewable sources. The Apulian context best fits this objective, by virtue of the high percentage of cultivated fields of olive trees and the consequential great quantity of pruning residues that are usually unemployed and burned on fields.

In the European Community, olive groves are mostly present in the Mediterranean region. In fact, Mediterranean countries, led by Spain, produce 10 million tons of olives per year, which is 75% of the world production [5]. The Italian cultivation of olive trees is diffused above all in southern and insular regions where about 80% of the Italian production of olives and oil olive is obtained. As a matter of fact, the Italian region having the greatest extension of olive cultivated land is Apulia with 377.550 hectares, followed by Calabria (194.887 ha) and Sicily (161.967 ha). Ever-increasing advances and research studies on the olive oil production technology demonstrate the importance of olive oil production upon Italian economy [6].

Every year, in these zones, farmers have the problem of disposing, at their own expenses, of tons of pruning residues. In [7], the management of pruning residues is considered: the authors argue that pruning residues, despite having generally represented a disposal problem, can become a real opportunity for additional revenue if an energy recovery of such wastes is performed, using them as fuels for energy production; thus, in addition to eliminating the problem of disposal, the future commercialization of such agricultural wastes can be a source of income rather than a cost for farmers.

In the past, the inefficiency and low availability as well as the high costs of harvesting machines were all limiting factors in exploiting tree pruning residues. A large part of such residues was usually burned on fields, while only the thickest branches were recovered by farmers and used as fuel-wood [8, 9]. A change in farmers' mentality is now possible by virtue of recent advances in designing harvesting machines, which are more reliable and efficient than in the past, thus allowing farmers to be able to perform collection and harvesting processes effectively in terms of cost and time. In this regard, new industrial pruning harvesters capable of overcoming the limits of common small units were tested in [7], showing that the introduction of the industrial technology can be instrumental in increasing the energetic use of pruning residues. More effective strategies in managing such residues can help farmers better exploit older and smaller size machines, especially in small farms and in those groves where steep terrain and/or irregular spacing do not allow the profitable use of large industrial harvesting units [7].

2.2 Availability of feedstock and plant demand

This section aims to assess whether the availability of raw material meets the requirements of the plant presented here, which is going to be realized at Bari Airport.

It should be noted that the by-product present on a field cannot entirely be used for energetic valorisation because of the permanence time on the field and weather conditions during the harvesting as well as the plot of the land (dimension and form). In order to evaluate the net potential availability of olive tree pruning residues in Apulia accounting for all of these factors, a valid calculation method was recently proposed in [10, 11]. This method quantifies the quantity of olive tree pruning residues per hectare per year by means of the following equation:

$$Q_{pr} = Q_{ol}\frac{Y}{f}\cdot\frac{a}{100} \qquad \textbf{\textit{(1)}}$$

where Q_{pr} ~~(t/year/hectare)~~ is the mass of wet by-product (pruning residues) per hectare that is yearly obtainable, Q_{ol} ~~(t/year/hectare)~~ is the mass of olives per year obtained in the field, *Y* is the ratio of the overall by-product to the overall olive yield, *f* is equal to the pruning frequency per year and *a* is the potential availability ~~(%)~~ that takes into account the characteristics of harvesting techniques and field as well as climatic conditions.

Once coefficients *a* and *f* are known, equation (1) allows calculating the precise value of Q_{pr} achievable from a specific zone, provided that factor *Y* is properly estimated. To accomplish this task, two equations have been retrieved in [10], specifically one for the provinces of Bari and Foggia and the other one for the provinces of Lecce, Brindisi and Taranto. These formulations calculate the by product/product ratio, *Y*, as a function of the yield of olives, Q_{ol} ~~(expressed in t/year/hectare)~~:

$$Y = 0{,}566 + \frac{1{,}496}{Q_{ol}} \quad \text{for Bari and Foggia} \tag{2}$$

$$Y = 0{,}365 + \frac{1{,}401}{Q_{ol}} \quad \text{for Taranto, Lecce and Brindisi} \tag{3}$$

Using Equations (1), (2) and (3), it is possible to depict the regional map of the net pruning residues available per year, as shown in Fig.1. In addition, Fig.1 shows their energetic potential ~~(expressed in tep/year)~~, which was obtained by multiplying Q_{pr} and the lower heating value (H_i) calculated through equation (4):

$$H_i = H_{dry}\left(1 - \frac{U}{100}\right) \tag{4}$$

where H_{dry} is the lower heating value of dry biomass ~~(kcal/kg)~~ and averages 4200 kcal/kg for pruning residues, U is the average humidity percentage present in the residuals collected on the field. This approach has general validity and can be applied to other zones of Italy as well as other European countries, provided that coefficients a, U and f, along with the relation between Y and Q_{ol}, are tuned in relation to the specific zone.

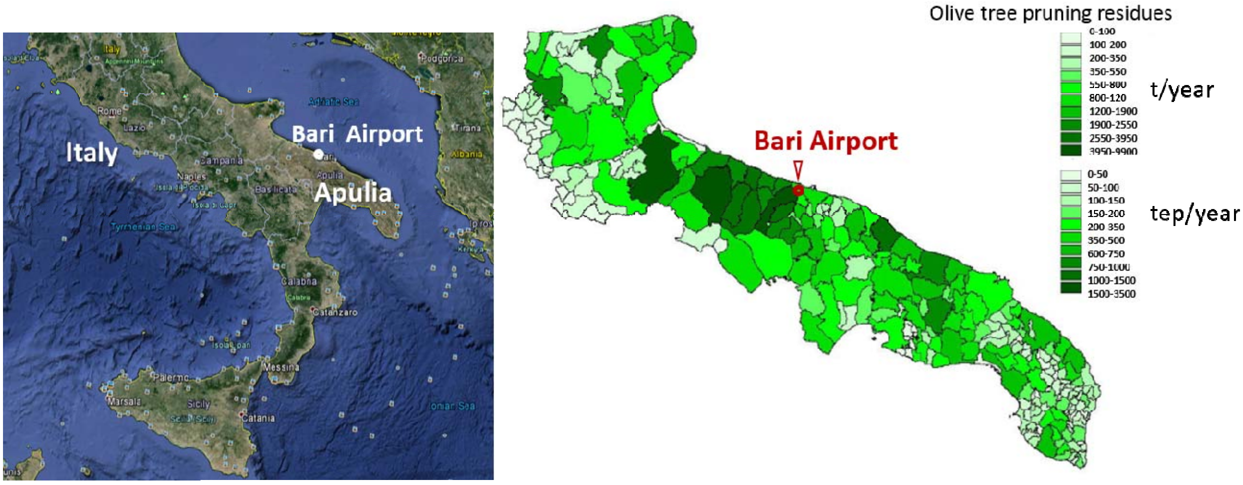


Figure 1: Plant location along with the distribution of olive pruning residues (t/year) and their energetic potential (tep/year) in Apulia.

The plant has been designed to ensure an electrical power (P_{el}) of about 280 kW. Using the expression of the electrical efficiency (η_{el}) and knowing the lower heating value of the fuel, the quantity of biomass needed for the plant operation covering a period of a year can be retrieved from the analytical expression of η_{el} :

$$\eta_{el} = \frac{P_{el}}{\dot{m}_b H_l} \qquad (5)$$

where $\dot{m}_b$ denotes the fuel mass flow rate. Considering that the plant is expected to operate 8000 hours per year and that its electrical efficiency is equal to 11,2% (as reported in the following section), and assuming the lower heating value of pruning residues present on fields equal to 2540 kcal/kg (according to equation 4 and assuming 40% humidity remained in residuals on fields), it results that $\dot{m}_b$ is equal to 6800 t/year.

Such a feedstock demand must fully be satisfied by the farms surrounding the airport. In this regard, Table 1 reports the production of tree pruning residues in the municipalities nearest the plant location (average distance < 20 km), along with their average distances from the plant. The quantities of pruning residues in each municipality were calculated by multiplying the hectares of land covered by olive trees and the value of Q_{pr} resulting from equation (1). The total production of pruning residues resulting from Table 1 is 12.656,02 t/year, which is well above the plant demand, thus demonstrating that a very small area is sufficient to fully satisfy the plant demand. In particular, the complete production of tree pruning residues in Modugno (569,47 t/year), Bari (771,18 t/year) and Bitonto (4.986,49 t/year) together with a small part of the production in Giovinazzo (472,86 t/year) are capable of satisfying the annual demand of the plant. Only taking into account these four municipalities, the average distance from the plant can be calculated as a weighted mean (in which the weights are the quantity of tree pruning residues) and results to be equal to 10,1 km.

Town	Tree pruning residues production (t/year)	Average distance (km)
Modugno	569,47	9
Bari	771,18	10
Bitonto	4.986,49	10
Giovinazzo	1.937,61	13
Bitetto	1.292,99	15
Bitritto	423,23	15
Binetto	337,58	18
Palo	2.337,47	15
Tot	12.656,02	-

Table 1: Tree pruning residues production in the nearest municipalities and their distances from the plant

3. DESCRIPTION OF THE PLANT

3.1 Electrical and thermal demands of the airport

The designed plant is a tri-generative system employing a commercially available ORC for simultaneous production of electricity and useful heat combined with an absorption chiller used to generate chilled water for air conditioning. Figure 2 depicts the thermal power required by the airport buildings during the year: it is concentrated in months comprised between November and April with a maximum demand of 410.000 kWh in January. The electrical demand of the airport, as depicted in Figure 3, is always present during the year and is subjected to an increase in the summer season, due to the air conditioning, with a peak of 1.000.000 kWh in July and August.

In the hot seasons (May, June, July, August, September, October), chilled water is needed to cool the buildings of the airport, whilst the thermal power required by the thermal users of the buildings is null. Contrarily, in the cold seasons (November, December, January, February, March, and April) the demand for cooling power is zero, while the buildings need useful thermal power. Because of such a thermal and cooling demand of the buildings during the year, it is not possible to perform a complete tri-generation, with the power plant assuming a combined cooling and power (CCP) configuration in the hot season and a combined heating and power (CHP) configuration in the cold season.

The power plant has been designed in order to satisfy the maximum thermal demand, which occurs in January. Considering the overall number of hours over which this thermal demand is distributed, the maximum thermal power provided by the plant must be equal to about 1500 kW. In a similar way, the maximum cooling power achievable by the plant has been set equal to the maximum cooling power demanded by the buildings in July, namely 500 kW. As a result, the absorption chiller of the plant has been chosen so as to provide a maximum cooling power of 500 kW.

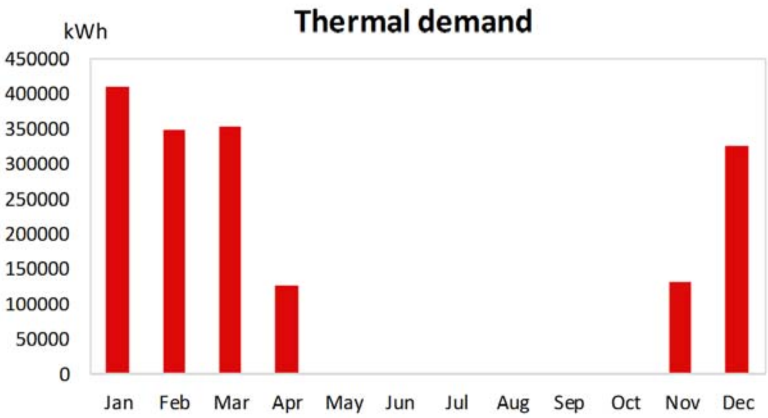


Figure 2: Airport thermal demand.

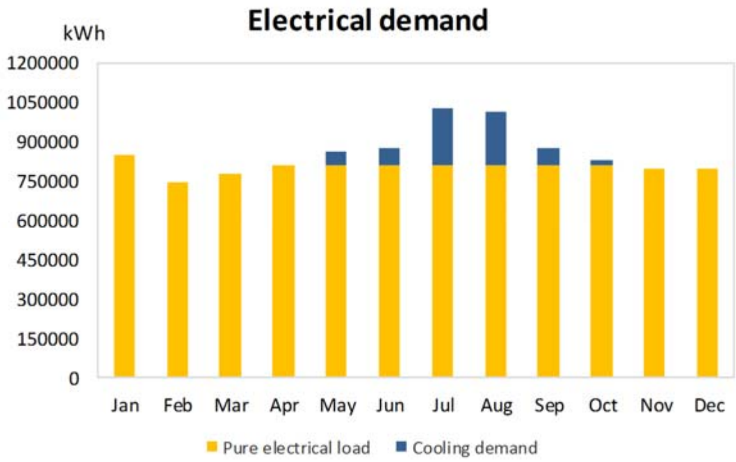


Figure 3: Airport electrical demand.

3.2 Plant layout and components

Figure 4 shows the layout of the plant along with the state point information. The main sub-systems of the plant, namely the biomass combustor, the ORC unit, the thermal users and the absorption chiller are analysed in the following sub-sections.

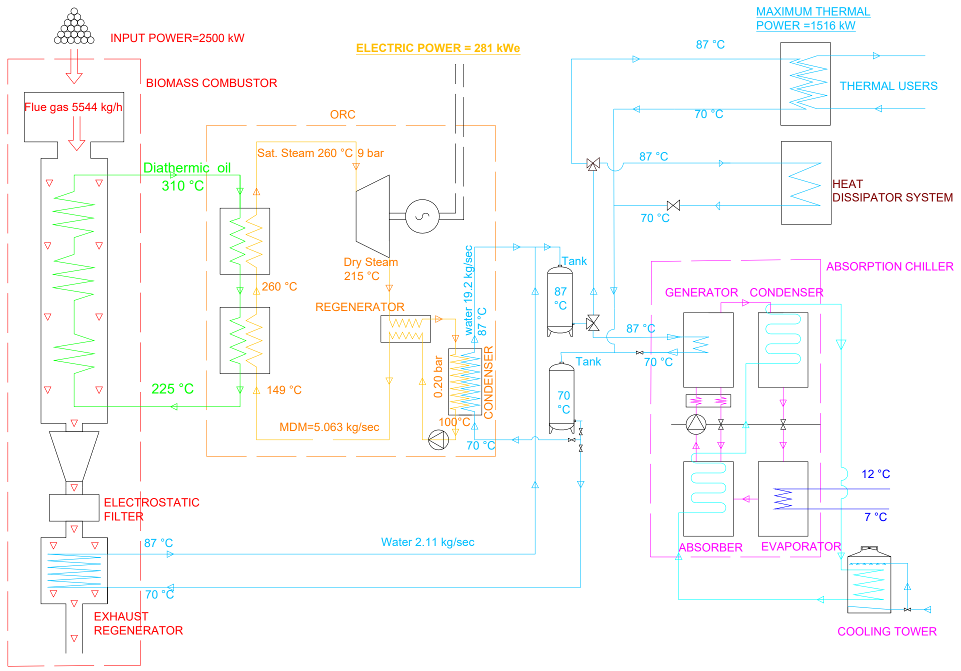


Figure 4: Plant layout with state point information

<u>BIOMASS COMBUSTOR</u>

On the left of Figure 4, the schematic representation of the biomass combustor (dashed red box) is reported, where the top black box indicates the combustion chamber. This is fed with pre-dried pruning residues by means of a pneumatic system, which allows burning bigger size pieces of wood as well as leaves and tree barks.

The biomass combustor is equipped with radiative and convective heat exchangers at its top for transferring heat from the flue gases generated from the combustion to the diathermic oil (denoted by the green line), thus increasing its temperature. After exiting the heat exchanger, the flue gases are subjected to particulate and ash elimination. To accomplish this task, a cyclone and an electrostatic filter, which is at present the best method of separation for the smallest particles, are placed downstream of the heat exchanger.

Before being discharged into the atmosphere, the flue gases flow through a final heat exchanger (referred to as the exhaust regenerator) which allows increasing the overall efficiency of the plant by recovering most of the residual thermal energy of the exhaust gases.

In order to reduce the NO_x emission (the limit value established by the normative is 200 mg/Nm^3), the strategy consists in the introduction of a certain quantity of urea in the combustion chamber, so that NO_x can react with the injected urea to form molecular nitrogen. To optimize the chemical reaction between urea and

NO_x , the temperature and reaction time must properly be controlled. The best range of temperature is between 800 and 1100 °C, with the optimum being equal to 1000 °C, while the best residence time ranges from 0,2 to 0,5 seconds.

<u>ORC</u>

The choice of an ORC system results from its peculiar characteristics, specifically: the turbine isentropic efficiency can be as high as 90%, the turbine can rotate at very low rotational speed and, as a result, can directly be connected to the electric generator without the need for a gear reducer. Furthermore, the turbine blades are subjected to low usury thanks to humidity absence during the steam expansion, and the system ensures short time for maintenance and long life of the components because this technology is nowadays mature and reliable. All these advantages have contributed to make ORC systems the most widespread technology for small-scale combined heating and power generation from biomass [12-13]. However, thanks to recent technological advances in designing gas to gas heat exchanger [14-16] and micro water-steam expanders, it was demonstrated in [17] that the employment of small combined cycles as a valid alternative to ORC systems for CHP from biomass will be feasible in the near future and will be able to guarantee competitive thermodynamic performances.

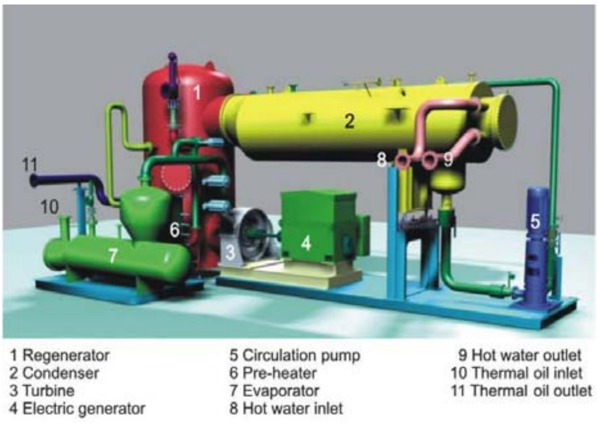
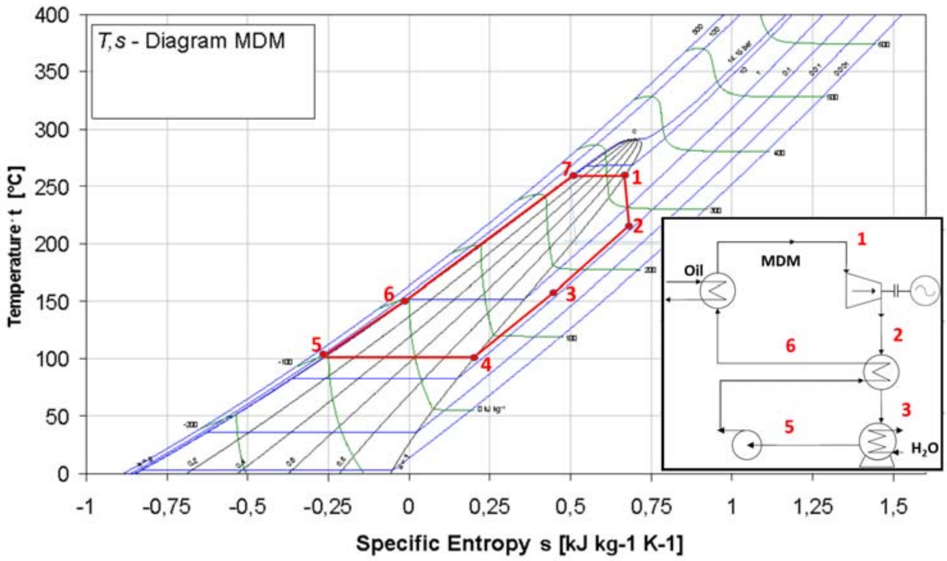


Figure 5: CAD representation of the ORC unit [18].

A CAD representation of the selected ORC unit is shown in Fig. 5. This unit is commercially available [18] and has been selected among commercially available units in order to satisfy the maximum thermal demand of the airport while ensuring the maximum possible electrical efficiency. In fact, the unit is capable of generating an electrical power of about 281 kW with an efficiency of 16.4%, which is very high level of performance despite the small-scale application and despite the very high condensation temperature required by the thermal users. The thermodynamic cycle of the ORC is reported in Fig. 6 along with all the values of pressure, temperature and enthalpy; Fig. 7 shows the heat exchange both in the boiler (which is made up of an economizer and an evaporator) and in the condenser (which also comprises a de-superheater). Both graphs have been retrieved by the authors using the data provided by the manufacturer. More details regarding the performance parameters of the ORC unit are provided in Table 2.



MDM	5,063 kg/sec
T_1	260 °C
h_1	333,8 kJ/kg
P_1	9 bar
T_2	215 °C
h_2	274,6 kJ/kg
P_2	0,2 bar
T_3	159,9 °C
h_3	167,74 kJ/kg
T_4	100 °C
h_4	70,190 kJ/kg
P_4	0,2 bar
T_5	100 °C
h_5	-101,83 kJ/kg
T_6	149 °C
h_6	-4,464 kJ/kg
T_7	260 °C
h_7	202,62 kJ/kg

Legend:
T=temperature; h=enthalpy
P=pressure

Figure 6: Thermodynamic cycle of the ORC

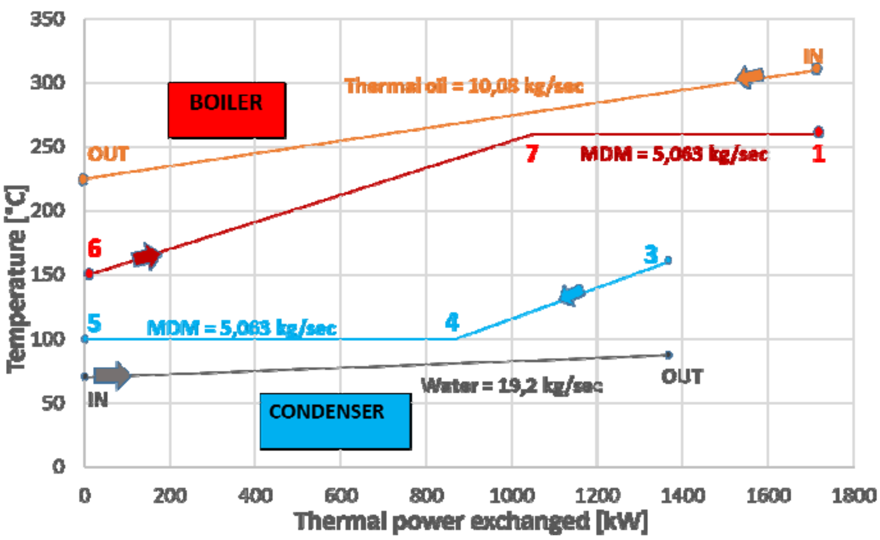


Figure 7: Temperature vs thermal power in the boiler (top) and condenser (bottom)

The proposed application is a high temperature configuration, as the heat source comes from the biomass combustion. As occurs in most of the commercially available ORC units to be used in high temperature applications (i.e. biomass combustion), the working fluid is not directly coupled to the flue gas, but a thermal oil is used as a thermal vector between the combustor and the ORC, in order to privilege safety and economic aspects. Indeed, the use of the thermal oil allows avoiding local overheating and allows the heat exchanger to operate at atmospheric pressure, as also discussed in [19]. Moreover, the adopted temperature (about 310°C) for the hot side of the thermal oil (therminol 66) ensures a very long oil life. The utilization of the thermal oil also allows operation without requiring the presence of licensed operators.

The working fluid is a siloxane, namely MDM (octamethyltrisiloxane, molecular formula = $C_8H_{24}O_2Si_3$, critical temperature = 290 °C, critical pressure =14.20 bar, molecular weight = 236.5 kg/kmol). The siloxanes are the most used molecules in high temperature CHP applications, because they have the desired characteristics that best fulfil the high working temperatures [20]. The use of MDM as the working fluid results from the fact that MDM is the most suitable in cycles having high condensation temperatures. In fact, in the proposed plant the condensation temperature must be of the order of 100 °C to satisfy the needs of the heating network (hot water at 87 °C is needed in the plant). Despite the very high condensation temperature, the use of MDM allows the back-pressure of the turbine to be kept as low as possible, by virtue of its very low condensation pressure at 100 °C (20 kPa). As a result, the working fluid can be expanded in the turbine to 20kPa, and, at this exit pressure, the temperature of the steam is still very high (215 °C). This temperature level makes the employment of the regenerator mandatory in order to maximize the efficiency of the cycle.

<u>THERMAL USERS AND ABSORPTION CHILLER</u>

In the condenser of the ORC system, the working fluid disposes of the remaining heat to the cooling water (azure line) which is used either in an additional heat exchanger for thermal uses or in the absorption chiller (purple dashed box) using a solution of lithium bromide salt and water for cold generation. When the thermal power produced by the plant exceeds the demand for chilled water or useful thermal power, the excess thermal power is dissipated through a heat dissipator.

In the configuration proposed, two insulated water tanks are used to regulate the flow of the hot water used as thermal vector for the absorption chiller and for the thermal user: a large part of the hot water (at 70 °C) is sent from the bottom tank to the condenser of the ORC cycle, while the remaining part is sent to the exhaust regenerator. The hot water exits these two devices at higher temperature (87 °C) and is conveyed into the top tank, which is used to distribute the hot water either to the thermal user or to the generator of the absorption chiller. Finally, the hot water at lower temperature (70 °C) exiting either the generator or the thermal user is delivered back to the bottom tank in order to have a continuous operation mode. In Figure 4, the heat dissipator system is depicted below the heat exchanger indicating the thermal users; the heat dissipator is activated by acting on a three-way valve, which is also capable of regulating the thermal power to be dissipated according to the demand of either the thermal users or the absorption chiller.

On the right hand side of Figure 4, it is possible to observe the components of the absorption chiller, specifically the absorber coupled with the generator, the condenser, the lamination valve and the evaporator. In the configuration proposed for the absorption chiller, a cooling tower is used to dispose of the heat transferred to the condenser coolant. The choice of an absorption refrigerator instead of a compressor refrigerator results from the fact that the former allows the recovery of the surplus heat; furthermore, an absorption refrigerator does not need a compressor to realize the refrigeration cycle, which results in a substantial reduction in the electric power compared to a standard compressor refrigerator. It should be noted that novel and effective studies have been conducted in order to recognise the optimum hot water temperature for absorption chillers [21, 22].

The selected unit is a commercially available lithium bromide absorber that is capable of providing the maximum efficiency (72%) with a hot water temperature of 87 °C. This choice was made in order to maintain the same condensation temperature of the ORC both in Summer and in Winter. This choice allows the ORC unit to operate constantly at its design conditions and allows the complexity of the regulation system to be reduced.

3.3 Efficiency analysis

All the components of the power plant shown in Fig. 4 are commercially available, and their performance parameters are clearly indicated by the manufacturer. Table 2 reports the specifications along with the setting chosen for the biomass combustor, the exhaust regenerator and the ORC system. As indicated in this table, a great part (2141 kW) of the input power (2500 kW) is transferred to the diathermic oil according to the efficiency of the heat exchanger (85,6%), while the residual thermal energy of the exhaust gases is partly recovered through the exhaust regenerator and is transferred to the hot water (maximum thermal power recovered = 150 kW). Not all the thermal energy transported by the diathermic oil (2141 kW) can be transferred to the ORC, because of the efficiency of the heat exchanger of the ORC system (80%); as a result, the thermal power in input to the ORC results to be equal to 1710 kW. For this value of input power, the chosen ORC system is capable of producing 281 kW_e, while a thermal power of 1366 kW is still available in form of hot water exiting the condenser. The overall efficiency (including both the electrical and the thermal power produced) of the ORC system, excluding the heat exchangers and the other components of the plant, is equal to 0,96.

The setting shown in Table 2 is valid both for the summer season, when only air conditioning is needed (combined cooling and power configuration), and for the rest of the year, when the absorption chiller is unnecessary and the thermal energy transferred to the water in the condenser can be recovered only for thermal use (combined heating and power configuration).

Table 3 reports the setting regarding only the former case (combined cooling and power configuration). In this case, it is noteworthy that cold water at 7 °C is available for the cooling system with a maximum cooling power of 500 kW. The electrical efficiency (η_{el}) is defined by equation (5) and is equal to 11,2%, while the overall efficiency (η_G) is 31,2% according to equation (6):

$$\eta_G = \frac{P_{el} + \dot{Q}_C}{\dot{m}_b H_i} \quad \textbf{(6)}$$

where $\dot{Q}_C$ denotes the cooling power. In contrast, Table 4 reports the setting regarding the latter case (combined heating and power configuration), when chilled water is not needed. In this case, a maximum useful thermal power of 1516 kW can be produced (35,5 kg/s of hot water at 87 °C) in January. The maximum overall efficiency, η_G , results to be equal to 71,8%, according to equation (7):

$$\eta_G = \frac{P_{el} + \dot{Q}_{th}}{\dot{m}_b H_i} \quad \textbf{(7)}$$

where $\dot{Q}_{th}$ denotes the useful thermal power.

The maximum potential of the proposed plant in the two different configurations is also illustrated by the bar charts of Figure 8 for completeness.

Plan component	Description	Value
Biomass combustor	Input power	2500 kW
	Thermal power transferred to the Diathermic-oil	2141 kW
	Heat exchanger efficiency	85,6%
	Mass flow rate of the flue gases	5544 kg/h
Exhaust regenerator	Flue gas temperature at the exhaust regenerator inlet	220 °C
	Flue gas temperature at the exhaust regenerator outlet	100 °C
	Maximum mass flow rate of water entering the exhaust regenerator	2,11 kg/s
	Water temperature at the inlet of the exhaust regenerator	70 °C
	Water temperature at the outlet of the exhaust regenerator	87 °C
	Maximum thermal power transferred to the water	150 kW
	Efficiency of the exhaust regenerator	81%
ORC	Thermal power transferred to the working fluid	1713 kW
	Gross electrical power of the steam turbine	300 kW
	Net electrical power	281 kW
	Turbine isentropic efficiency	85%
	ORC overall electrical efficiency	16,4%
	Mass flow rate of cooling water (condenser)	19,2 kg/s
	Temperature of the water at the condenser inlet	70 °C
	Temperature of the water at the condenser outlet	87 °C
	Thermal power achievable in the condenser	1366 kW
	ORC thermal efficiency	80%
	ORC efficiency (thermal+electrical)	96%

Table 2: Specifications of the biomass combustor, exhaust regenerator and ORC valid both for the combined cooling and power configuration and for the combined heating and power configuration

	Summer configuration (electricity + cooling)	
Absorption chiller	Maximum mass flow rate of hot water through the generator	9,77 kg/s
	Temperature of hot water entering the generator	87 °C
	Temperature of hot water exiting the generator	70 °C
	Maximum thermal power transferred to the generator	695 kW
	Maximum mass flow rate of cold water through the evaporator	23,89 kg/s
	Temperature of cold water at the evaporator inlet	12 °C
	Temperature of cold water at the evaporator outlet	7 °C
	COP	72%
Plant efficiency	Net electrical power	281 kW
	Useful thermal power	-
	Maximum cooling power	500 kW
	Electrical efficiency	11,2%
	Maximum overall efficiency	31,2%

Table 3: Specifications of the absorption chiller and efficiency parameters valid for the summer configuration (combined cooling and power configuration)

	Winter configuration (electricity + heating)	
Thermal user	Maximum mass flow rate of hot water available for thermal users	21,31 kg/s
	Temperature of hot water available for thermal users	87 °C
	Temperature of hot water returning to the bottom tank	70 °C
Plant efficiency	Net electrical power	281 kW
	Maximum thermal power available for thermal use	1516 kW
	Cooling power	-
	Electrical efficiency	11,2%
	Maximum overall efficiency	71,8%

Table 4: Specifications of the thermal users and efficiency parameters valid for the combined heating and power configuration

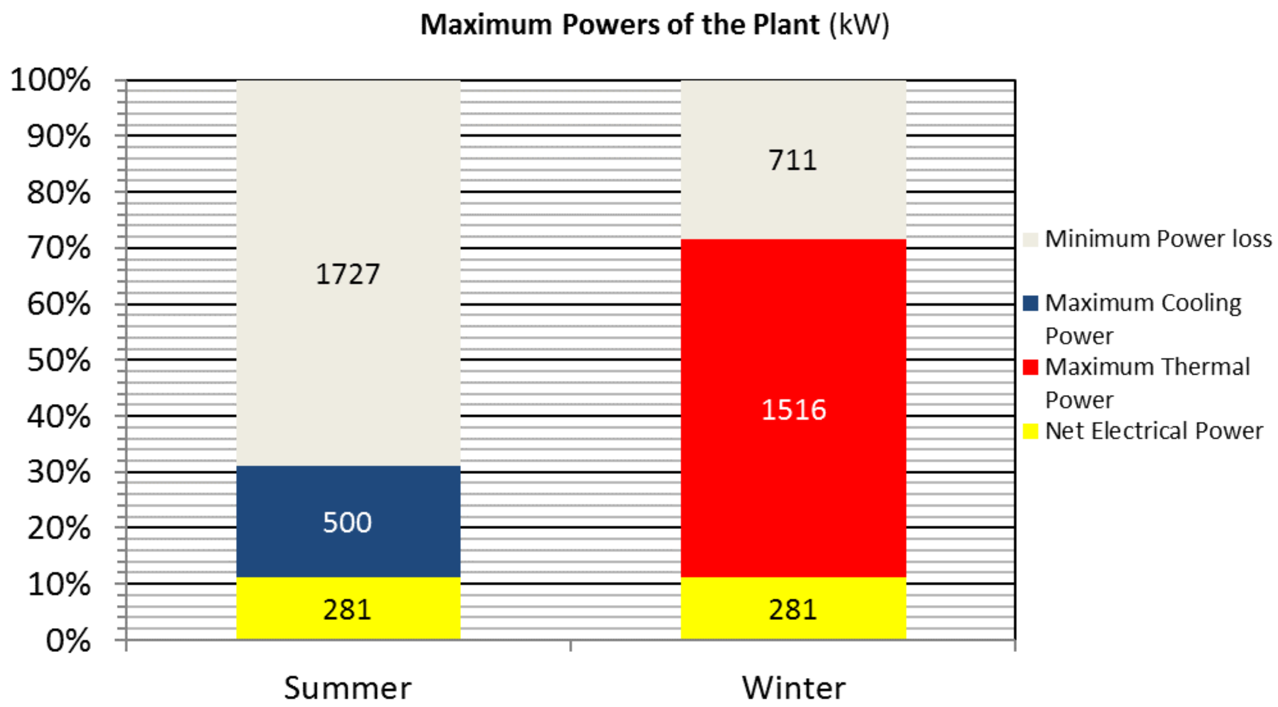


Figure 8: Maximum potentiality of the plant in the summer season (cooling and power) and in the winter season (heating and power).

Figure 9 shows how the overall efficiency of the plant changes with the months. The partial load strategy consists in producing the same electrical power (281 kWe), while dissipating the excess thermal and cooling power through proper dissipation systems. In this manner the ORC operates at its design conditions so that the efficiency of the ORC is not reduced at partial loads; as a result, the electrical energy obtained from biomass is always the maximum possible. This strategy is also justified by the large availability of feedstock in the zone surrounding the airport (see Section 2).

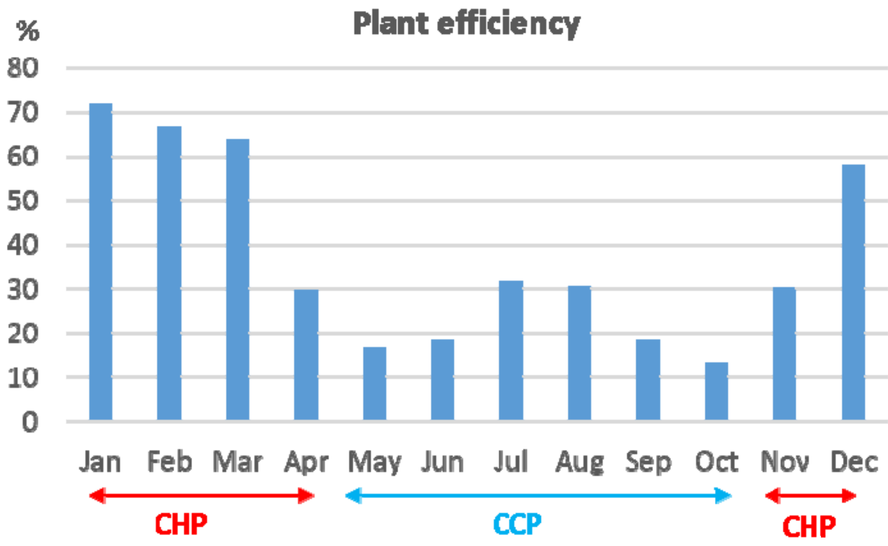


Figure 9: Overall effciency vs months

4. ECONOMIC ANALYSIS

In this section the economic advantages that the plant can ensure are analysed. In particular, the payback period (PBP), the net present value (NPV) and the internal rate of return (IRR) are evaluated. To accomplish this task, it is necessary to quantify the periodic cash flow of the investment, in terms of annual costs and incomings.

4.1 Cost estimation

The main costs to be sustained are the overall cost for the realization of the plant and the annual cost required for the procurement of the necessary feedstock.

The cost of the plant, given by the sum of the costs of the components and the installation costs, amounts to 2.900.000 €.

The yearly cost ~~for~~ due to the procurement of the necessary feedstock ($C_{feedstock}$), expressed in €/year, can be calculated as follows:

$$C_{feedstock} = \dot{m}_b * (C_h + C_t + C_c) \tag{8}$$

where $\dot{m}_b$ is the fuel mass flow rate, C_h is the harvesting cost ~~(expressed in €/t)~~, C_t is the transportation cost ~~(expressed in €/t)~~ and C_c is the chipping cost ~~(expressed in €/t)~~.

The cost of harvesting depends on the machines used for this purpose. In this analysis, a machine (referred to as the baler) capable of both collecting tree pruning residues and grouping them into cylindrical bales, as with the forage waste, is considered. This machine was constructed for forage and in a second time modified for olive tree pruning residues. A bale has a diameter of 1.50 m and a width of 1.20 m, the medium weight varies between 400 and 450 kg, and the time necessary to produce a bale is about 15 minutes. According to the specification provided by the manufacturer, the operation costs for the harvesting operation can be estimated to be $C_h = 26$ € /t.

The overall transportation cost per tons of feedstock (C_t) is given by the sum of the cost of the fuel required for the round trip (C_f) and the cost for loading and unloading the feedstock (C_l), divided by the weight of the feedstock transported (P_m):

$$C_t = \frac{C_f + C_l}{P_m} \qquad (9)$$

According to typical vehicles for transportation of feedstock, the maximum weight of feedstock that can be loaded on the vehicle amounts to $P_m = 18$ t.

To calculate C_f, the average speed of the vehicle during the round trip can be assumed equal to 30 km/h with a fuel consumption equal to about 40 €/h in the case of transporting 18 t of feedstock, which results in a fuel cost per km equal to 1,33 €/km. The distance of a round trip can be taken equal to the average distance of the farmers from the plant, namely 10,1 km (see Section 2.2). With these assumptions, C_f amounts to about 26,9 € (multiplying 1,33 €/km by 20,2 km, considering the round trip). With regard to C_l, the time to load and unload 18 t of feedstock can be assumed equal to 1 hour (45 minutes necessary to load and 15 minutes to unload); if these operations are performed manually, C_l averages 25 €, according to the average salary of a worker [23].

Hence, substituting $C_f = 26,9$ € , $C_l = 25$ € and $P_m = 18$ t in equation (9) results in a total transportation cost (C_t) equal to 2.9 €/t.

The chipping stage allows obtaining a solid biofuel in the form of chips with dimensions suitable for the biomass combustor. The cost of the chipping phase can be estimated to be equal to $C_c = 5$ € /t.

In conclusion, it has been demonstrated that C_h= 26 € /t , C_t= 2,9 € /t and C_c= 5 € /t. Substituting these values in Equation (8) and considering that $\dot{m}_b$ = 6800 t/year, the cost required for the procurement of the necessary feedstock amounts to $C_{feedstock}$= 230.500 €/year.

4.2 Incomings estimation

The main incomings are represented by the avoided costs of hot water ~~generation~~ and electricity generation. The first contribution can be calculated from the examination of the annual thermal demand of the airport shown in Fig. 2, which amounts to 1.680.000 kWh_{th}. Considering that 1 Nm^3 of methane averagely costs 0,30 € and that the quantity of methane required to produce 1.680.000 kWh_{th} is about 159.200 Nm^3 according to the current technology, it results that the cost avoided for thermal power production is equal to 47.760,00 €/year.

The avoided cost of electricity-results from the fact that the overall electrical energy required by the airport is partly provided by the power plant. The plant produces an electrical power of 281 kW over 8000 hours, so the overall electrical energy provided to the airport buildings results to be equal to 2.248.000 kWh/year. In addition, the plant allows saving an electrical energy of 610.000 kWh necessary for the cooling of the buildings (see Fig.3). Summing up these two contributions and considering that the current price of electricity in that area is 0,12 €/kWh, the overall avoided cost of electricity is 342.960,00 €/year.

Further incomings are given by government incentives, which can be grouped into two categories independent from each other. The first one is equal to 75% of the overall capital cost of the plant and regards CCHP biomass –fuelled plants built in the south regions of Italy with a capital cost comprised between 2 and 25 millions of Euros. With this incentive, the initial plant cost of 2.900.000,00 € is lowered to 725.000,00 €. The other one regards all CCHP biomass –fuelled plants and ensures a bonus per every KWh_e produced during the initial 15 years. The bonus is equal to 0.227€ /kWh_e in the first year and then is reduced by 2% per year.

4.3 Analysis of the investments

The estimation of costs and incomings achieved in Sections 4.2 and 4.3 allows evaluating the annual cash flow of the investments. Figure 10 shows the annual cash flow during a period of 15 years: the situation regarding the first kind of incentive is depicted in red, while the other case is plotted in blue.

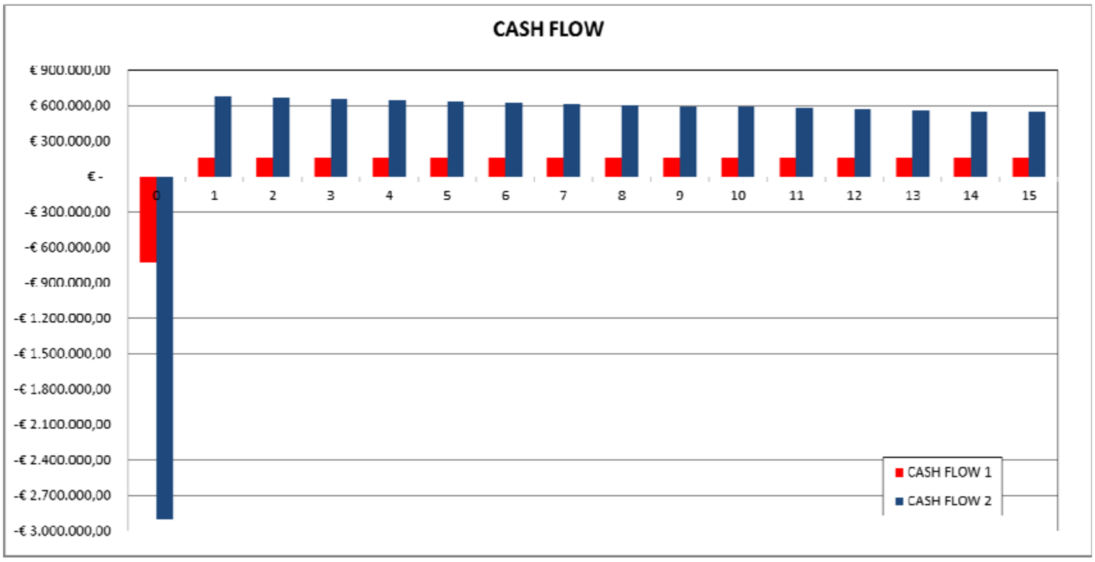


Figure 10: Annual cash flows of the investment vs number of years, considering the two typologies of government incentives separately.

The first type of incentives leads to having an initial outlay lower than the second type, but also a lower annual cash flow in all the subsequent years. This results from the fact that the first type of incentives only ensures a reduction in the initial cost of the plant, whilst the second type gives a bonus for each electrical kWh produced, thus ensuring additional annual incomings for the subsequent 15 years.

The calculation of the payback period and net present value can be instrumental both in evaluating the profitability of the investment and in recognizing which of the two typologies of government incentives is more suitable. These indicators are plotted in Figure 11 for both categories of incentives, with the assumption that the discount rate is equal to 8%. It can immediately be noticed that the investment has a PBP value of 6 years for both cases; furthermore, we can state that the second typology of government incentives (a bonus for each electrical kWh produced) ensures more gains than the first one. In fact, at the end of the 15th year the NPV is 646.399,00 € in the first case and 2.386.248,00 € in the second one.

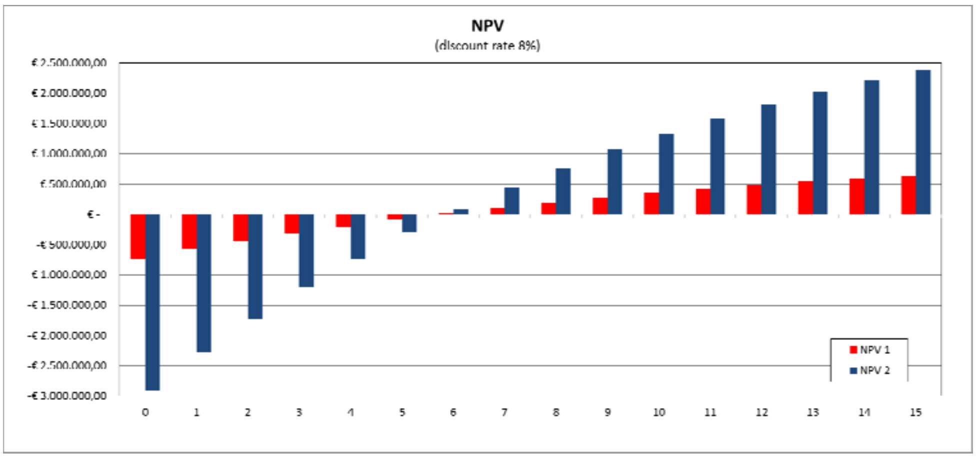


Figure 11: Net present value of the investment vs number of years for the two typologies of government incentives

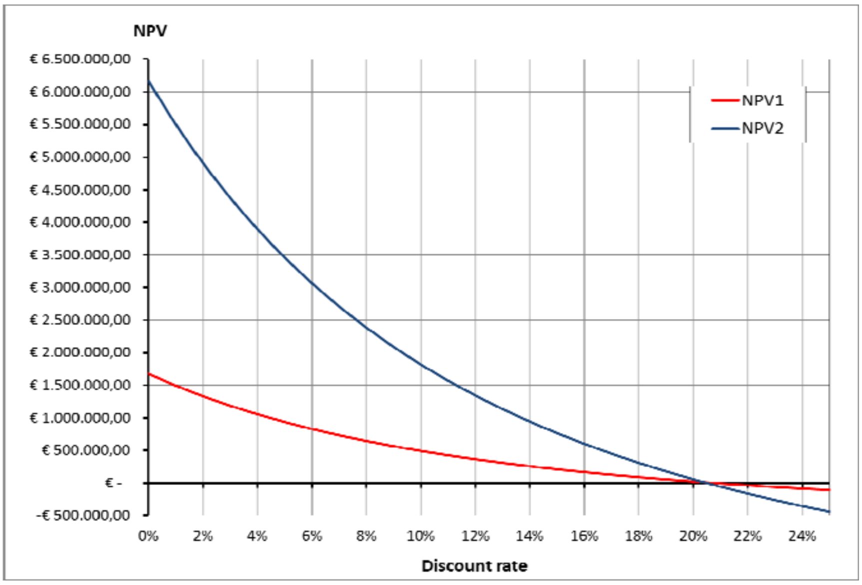


Figure 12: Net present value of the investment after the 15-th year, as a function of the discount rate for the two typologies of government incentives

These results can be generalized considering what happens at the changing of the discount rate. For both types of government incentives, Figure 12 shows the NPV of the investment after the 15-th year as a function of the discount rate. It is clear that this graph confirms that the second type of incentives is more convenient than the other one, regardless of the discount rate chosen.

From the examination of Figure 12, we can also appreciate the internal rate of return (IRR) of the investment. It is almost constant regardless of the typology of the incentive, being equal to about 21% in both cases. This value points out the profitability of the investment once again.

5. ECOLOGICAL CONSIDERATIONS

This final section evaluates the quantity of CO_2 that will not be released into the atmosphere after the proposed power plant is built at Bari Airport. To perform this evaluation, it must be considered that 1 Nm^3 of methane weighs 0,7 kg, and 2,75 kg of CO_2 are normally produced per kg of methane in a stoichiometric reaction.

With regard to the heat generation, the quantity of methane required to produce 1.680.000 kWh is 159.200 Nm^3, thus the annual quantity not released into the atmosphere will be 306.460 kg.

With regard to the electricity production, supposing a reference electrical efficiency of 0,60, it results that the methane necessary for the electrical generation is 316.050 kg. Thereby, the avoided release of CO_2 for electricity generation will be equal to 869.140 kg. Overall, the mass of CO_2 avoided per year will be 1.175.600 kg.

In conclusion, it results that the proposed tri-generative plant can be very important in the Apulia context from an ecological point of view. Furthermore, the plant can lead to a double ecological gain, because in addition to avoiding the combustion of fossil fuels for energy production, it can also avoid that a lot of olive pruning residues are burned on fields with considerable quantities of CO_2 released into the atmosphere. Such a practise is prohibited by the Italian law and produces a great quantity of dioxin because of the low temperature combustion, while the produced pollutants are almost completely eliminated in the biomass combustor of the proposed tri-generative plant.

6. CONCLUSIONS

For over twenty years ever increasing attention has been given to the ecological problem in national politics. One of the most effective ways to reduce CO_2 emissions is the use of biomass as fuel for energy production. This research is focused on the energetic use of agricultural wastes in Apulia, in particular olive tree pruning residues. At present, such agricultural residues are burned on Apulian fields (despite being prohibited by the Italian law) with a consequential loss of possible energy exploitation.

In the real case considered, pre-dried olive tree pruning residues are directly used as solid fuel in a tri-generative power plant of about 280 kW_e planned to be located near Bari Airport.

The Apulia context was analysed with respect to the availability of feedstock, finding that the resource of biomass present in a very small area surrounding the plant location is sufficient to satisfy the energetic needs of the plant. Afterwards, the plant was described in detail. It is composed of a biomass combustor, a co-generative ORC system and an absorption chiller, which ensures chilled water in the summer. Moreover, to reduce the quantity of pollutant components like NO_x and CO, an electrostatic filter will be positioned downstream of the exhaust regenerator

In the winter season, when the production of chilled water is unnecessary, the plant will be able to produce a maximum thermal power of 1516 kW in the form of hot water at 87 °C along with a net electrical power of 281 kW. In contrast, part of the thermal power can be transferred to the generator of the absorption chiller with the aim of producing chilled water (maximum cooling power of 500 kW) in the summer season. In the former case (combined heating and power configuration), the overall efficiency of the plant is 71,8%, while, in the latter case (combined cooling and power configuration) the plant is able to produce electricity and cooling power with a maximum overall efficiency of 31,2%.

The main economic advantages come from the avoided costs of electricity and methane necessary for generating the thermal power. Two typologies of government incentives have been considered: according to the first one, the government finances a percentage of the plant cost, contrarily, according to the other one, the government provides a bonus for every electrical kWh produced. In both cases, the payback period is 6 years and the internal rate of return is about 21%, highlighting that the proposed project is highly convenient from an economic point of view. From an ecological point of view, the plant is remarkably eco-efficient, ensuring a reduction of 1.175.600 kg/year in CO_2 emissions.

Although this research activity is concerned with a specific zone, namely the area surrounding Bari Airport, the results can be applied to other zones of the Mediterranean region, which has continuous availability of residues from olive tree pruning practices.

REFERENCES

1. Climate Change 2014: Mitigate of climate change - IPCC Working Group III Contribution to AR5
2. Scarlat, N., Dallemand, J. F., Motola, V., & Monforti-Ferrario, F. (2013). Bioenergy production and use in Italy: recent developments, perspectives and potential. *Renewable Energy*, *57*, 448-461.
3. Silvestri, S., Cristoforetti, A., & Mescalchin, E. (2011). Recovery of pruining waste for energy use: agronomic, economic and ecological aspects. Central European Biomass Conference 2011, 26th – 29th January, Graz - Austria .
4. Amirante, P., & Pipitone, F. (2000). Technological innovations for mechanical harvesting of olives. Olea europaea L. - Apulia - Basilicata – Sicily, 3-9 November 2000.
5. Azbar N. (2004). A Review of Waste Management Options in Olive Oil Production. Critical Reviews in Environmental Science and Technology, 34:209–247, 2004.

6. Amirante, P., Clodoveo, M.L., Dugo, G., Leone, A., & Tamborrino, A. (2005). Advance technology in virgin olive oil production from traditional and de-stoned pastes: influence of the introduction of a heat exhanger on oil quality. Food Chemistry, 98, 797-805.
7. Spinelli, R., & Picchi, G. (2010). Industrial harvesting of olive tree pruning residue for energy biomass. Bioresource technology, 101(2), 730-735.
8. La Cal Herrera, J. A., Jurado, F., & Ogayar, B. (2012). A New Model of Energy Valorization for Olive Grove By-Products Based on the Gasification Technology Integrated in an Olive-Oil Mill. International Journal of Green Energy, 9(7), 661-672.
9. Requejo, A., Rodríguez, A., González, Z., Vargas, F., & Jiménez, L. (2012). Ethanol pulping as a stage in the bio-refinery of olive tree prunings. BioResources, 7(3).
10. Pantaleo, A., Carone, M. T., & Pellerano, A. (2009). Olive residues to energy chains in the Apulia region part I: biomass potentials and costs. Journal of Agricultural Engineering, 40(1), 37-47.
11. A.I.G.R. (Associazione Italiana di Genio Rurale), Potenzialità energetica da biomasse nelle regioni italiane – Rapporto conclusivo - introduzione e parte prima, (1994) Contratto A.I.G.R. - ENEA del 03 dicembre 1992 - Pratica 00073, aprile 1994.
12. Wei, D., Lu, X., Lu, Z., & Gu, J. (2007). Performance analysis and optimization of organic Rankine cycle (ORC) for waste heat recovery. Energy conversion and Management, 48(4), 1113-1119.
13. Dai, Y., Wang, J., & Gao, L. (2009). Parametric optimization and comparative study of organic Rankine cycle (ORC) for low grade waste heat recovery. Energy Conversion and Management, 50(3), 447 576-582.
14. Catalano, L. A., De Bellis, F., Amirante, R., & Rignanese, M. (2011). An immersed particle heat exchanger for externally fired and heat recovery gas turbines. Journal of Engineering for Gas Turbines 457 and Power, 133(3), 032301. 458
15. Amirante, R., & Tamburrano, P. (2014). High Temperature Gas-to-Gas Heat Exchanger Based on a 459 Solid Intermediate Medium. Advances in Mechanical Engineering, 2014.

16. Catalano, L. A., De Bellis, F., Amirante, R., & Rignanese, M. (2010, October). A High-Efficiency Heat Exchanger for Closed Cycle and Heat Recovery Gas Turbines. In ASME Turbo Expo 2010: Power for Land, Sea, and Air (pp. 357-367). American Society of Mechanical Engineers.

17. Amirante, R., & Tamburrano, P. (2015). Novel, cost-effective configurations of combined power plants for small-scale cogeneration from biomass: Feasibility study and performance optimization. Energy Conversion and Management, 97, 111-120.

18. Turboden s.r.l. Street Cernaia 10, 25124 Brescia, Italy. http://www.turboden.eu. (accessed on March 2015).

19. Drescher, U., & Brüggemann, D. (2007). Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants. *Applied Thermal Engineering*,*27*(1), 223-228.

20. Fernández, F. J., Prieto, M. M., & Suárez, I. (2011). Thermodynamic analysis of high-temperature regenerative organic Rankine cycles using siloxanes as working fluids. Energy, 36(8), 5239-5249.

21. Lecuona, A., Ventas, R., Venegas, M., Zacarías, A., & Salgado, R. (2009). Optimum hot water temperature for absorption solar cooling. Solar Energy, 83(10), 1806-1814

22. Darkwa, J., Fraser, S., & Chow, D. H. C. (2012). Theoretical and practical analysis of an integrated solar hot water-powered absorption cooling system. Energy, 39(1), 395-402.

23. Cozzi, M., Di Napoli, F., Viccaro, M., & Romano, S. (2013). Use of forest residues for building forest biomass supply chains: Technical and economic analysis of the production process. Forests, 4(4), 1121-1140